Document made available under the Patent Cooperation Treaty (PCT)

International application number: PCT/AU05/000154

International filing date: 08 February 2005 (08.02.2005)

Document type: Certified copy of priority document

Document details: Country/Office: AU
Number: 2004900618
Filing date: 09 February 2004 (09.02.2004)

Date of receipt at the International Bureau: 22 February 2005 (22.02.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

World Intellectual Property Organization (WIPO) - Geneva, Switzerland
Organisation Mondiale de la Propriété Intellectuelle (OMPI) - Genève, Suisse

PCT/AU2005/000154

Australian Government

Patent Office
Canberra

I, JANENE PEISKER, TEAM LEADER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. 2004900618 for a patent by THE AUSTRALIAN NATIONAL UNIVERSITY as filed on 09 February 2004.

COMMONWEALTH OF AUSTRALIA
AUSTRALIA
PATENT OFFICE

WITNESS my hand this
Eighteenth day of February 2005

JANENE PEISKER
TEAM LEADER EXAMINATION
SUPPORT AND SALES

Regulation 3.2

The Australian National University

AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

for the invention entitled:

"A shape memory alloy actuator"

The invention is described in the following statement:

A shape memory alloy actuator

Field of the invention

The present invention relates to a shape memory alloy actuator, and more particularly, to a controller for a shape memory alloy actuator.

Background of the Invention

Shape memory alloys (hereinafter referred to as "SMA"s) are a specific group of alloys sharing a particular physical property. In a solid state, they have two different crystalline states or phases, a low-temperature phase called martensite, and a high-temperature phase called austenite.

A material formed from a SMA and having a largely martensite phase typically has a low yield strength, and can be subjected to significant strains and plastic deformation by the application of a relatively small force. If the deformed material is then heated so as to revert to a largely austenite phase, the material recovers its original shape. The shape recovery of SMAs is accompanied by a large force that is capable of doing a significant amount of mechanical work, and it is this property of SMAs that is utilised by SMA actuators to convert electric or heat energy into mechanical energy.

Typically strains of up to about 4% can be fully recovered from SMAs having a largely martensite phase. While strains up to 8% may be applicable to SMAs such as nitinol for example when cool, generally actuators don't use strains greater than 4%, as strains higher

than this can cause rapid fatigue. As such, the strains used for most alloys having a largely martensite phase are typically less than 4%. Austenite phase SMAs typically are incapable of tolerating strains of such a large magnitude.

SMA actuators generally operate by stretching at least one SMA portion having a largely martensite phase, typically in the form of either a straight wire or coil, by the application of an external force, typically from a spring, a weight or another actuator. The wire is then heated, whereupon it converts to a substantially austenite phase and contracts with a considerable force that can be used to perform mechanical work. When the wire has cooled sufficiently, it will revert to a substantially martensite phase, whereupon it may be again stretched and plastically deformed by the application of an external force (such as that applied by a spring, weight or another actuator as above).

The speed at which the wire may be contracted and extended, and hence the actuation speed of the actuator, are limited by both the cooling and heating rates of the wire. The rate at which the wire is cooled may be improved by using water or forced-air cooling for example, or simply even by using thinner wire.

As for heating of the wire, this is usually accomplished by Joule heating whereby an electric current is passed through the wire, with the wire's resistivity causing heat generation. While the rate at which the wire is heated may be increased by applying a larger current, this is not done in practice due to the associated risk of overheating the wire and thereby permanently damaging the SMA. For this reason, SMA data sheets usually

specify a safe limit current (equivalent to a safe power per unit length of wire) which can be left on indefinitely without overheating the SMA. Electric heating systems for heating the wires formed from SMAs are usually designed to deliver no more than this safe limit current, although it will be appreciated that an electric current beyond the safe limit current does not itself damage the SMA; it is temperature of the wire that must not exceed a certain level.

Summary of the Invention

Preferred embodiments of the present invention seek to provide a controller for improving the speed of actuation of SMA actuators by increasing the rate at which they are heated.

In accordance with one aspect of the present invention, there is provided a controller for a SMA actuator, the SMA actuator including at least one SMA portion, the controller including:

an electric power source for applying an electric current through the SMA portion;

a sensor to detect change in the electric resistance of the SMA portion, and

a regulator for controlling the magnitude of the applied electric current, said regulator applying a first current above a safe limit current for the SMA portion until a selected change in said electric resistance is detected and applying a second current less than said first current after said change is detected.

In one embodiment according to the present invention, the second current is less than or equal to the safe limit current for the SMA portion.

Preferably, the change in the electric resistance of the SMA portion is detected by measuring the electric resistance of the SMA portion.

Preferably, the electric resistance of the SMA portion is determined substantially continuously or at least at frequent intervals.

Preferably, the selected electric current supplied by the regulator is preferably maintained below a maximum limit current of the electric power source.

In one practical form of the invention, the SMA portion may be a straight wire for example. When the wire is cool, having a substantially 100% martensite phase, the wire may be relatively easily plastically deformed by the application of a relatively small force. The wire may be then later heated by passing an electric current through the wire, such that the wire contracts and returns to its original shape. When the wire is heated sufficiently, the wire will have a substantially 100% austenite phase. To prevent damaging the SMA however, the temperature is maintained below a temperature associated with the SMA at which thermal damage will occur.

In another form of the invention, the SMA portion may be substantially a coil.

The resistances of SMA phases generally vary considerably with alloy composition. For the SMA sold under the trade mark "Flexinol" for example, which is made of the alloy

nitinol, the resistivity is about 15% to 20% higher in the martensite phase compared with the austenite phase. It will be appreciated that this will not be true for all SMAs. It is expected that this difference would be subject to considerable variation between alloys of different compositions, and it is contemplated that there may even exist alloys where the martensite phase has a lower resistance than the austenite phase. In any case, the present invention is not limited by which phase has a higher resistance. Rather embodiments of the present invention may be realised when the resistances of the phases are different and this difference is sufficiently large so as to serve as a useful measurement of the temperature of the SMA. As will be described below, a range for the temperature of a SMA portion can be determined from the measured resistance.

SMAs generally exhibit a quite large thermal hysteresis, whereby the martensite phase starts changing to austenite phase upon heating at a higher temperature than that at which austenite phase starts changing to martensite phase upon cooling. The magnitude of the hysteresis generally varies with the alloy type, but typically is within the range of about 10 to 50 degrees Celsius. While this means that the electric resistance cannot be used to directly establish the exact temperature of the SMA, it is nevertheless still possible to identify a range of temperatures that are consistent with a given electric resistance, and thereby to identify upper and lower temperature limits for a given electric resistance. This allows a safe resistance, preferably having a selected safety margin, at which the SMA will not overheat to be identified.

From the safe resistance, a safe resistance range may be identified for heating the wire without overheating and permanently damaging the wire. The above identified safe resistance will effectively be either an upper limit or lower limit of this safe resistance range. When the austenite phase exhibits a lower resistance than the martensite phase for a given alloy, electrical resistances corresponding to when the wire is not overheated will be of a larger magnitude than those at which the wire has potentially been overheated and as such the safe resistance will define a lower limit of the safe resistance range. Conversely, when the austenite phase exhibits a higher electrical resistance than the martensite phase, electrical resistances corresponding to when the wire is not overheated will be of a lesser magnitude than those at which the wire has potentially been overheated, and the safe resistance will define an upper limit for the safe resistance range.

By adjustably limiting the electric current applied to the wire whenever the resistance of a SMA portion falls outside of the identified safe resistance range of the SMA portion, the temperature of the wire may be maintained below the temperature at which thermal damage of the SMA portion will result from overheating. This allows the wire, by applying an electric current of maximum safe magnitude to be heated at a quicker, and preferably approaching optimal, rate.

There is often quite a large gap between the top of the operating temperature range (ie. the temperature range over which the phase transformation occurs) and the temperature at which thermal damage will occur. For wires formed from the alloy nitinol for example, the top of the operating temperature range is about 100 degrees centigrade, but the alloy

can withstand temperatures above 200 degrees centigrade without sustaining thermal damage. According to an embodiment of the present invention, it is quite acceptable for the temperature of the SMA to rise above its operating temperature range, and even for the heating system to continue passing a current through the SMA, so long as the current is limited to no greater than the safe limit current whenever the measured resistance lies outside the safe resistance range.

Preferably the magnitude of the current passing through the SMA portion varies smoothly as a function of measured resistance instead of changing abruptly in response to the change in the electric resistance, the smooth variation occurring over a defined portion of defined range of resistance values.

It will be appreciated that the resistance of a piece of metal varies with its dimensions, as would be the case for a wire forming part of a typical SMA actuator that reciprocally extends and contracts (a stretched wire will have a higher resistance simply because it is longer). At higher temperatures of the SMA (the area of interest) the strain on the SMA (around 1% for example) should be relatively small and correspondingly strain induced variations should also be relatively small. Thus, the strain induced effect on the resistance of a largely austenite phase SMA is typically quite small in comparison to resistance changes due to temperature associated phase changes. While strain induced variations would still need to be accounted for, they do not effect the resistance of a hot (austenite) SMA to such an extent that these variations undermine the ability to determine a practical range for the temperature of an SMA portion from a measured electric resistance.

The net effect of embodiments according to the present invention is faster motion when compared with previous control schemes. So long as an actuator is sufficiently cool, as indicated by its electrical resistance falling within the determined safe resistance range, the new control system can apply currents greatly in excess of the actuator's safe limit current, causing quicker heating, and therefor correspondingly a rapid phase change within the actuator and a rapid development of motive force. If the electrical resistance departs from the safe resistance range however, the control system can no longer be sure that the actuator is not overheating, and so the current drops to a safe level. As such, applying a large current, even if in excess of the safe limit current, across the wire is therefor safe until the resistance of the wire departs from the range of safe resistances. At that point, the current must be reduced or else the SMA may overheat.

Typically the resistivity of a particular SMA phase is determined from an appropriate data sheet. This relies on the assumption that all actuators made in a particular batch, or to a particular design, are the same. The expected values, or those measured from a representative sample, for the electrical resistances of the phases are published in the data sheets.

Preferably however, these values are obtained by measurement, wherein the controller has an initialisation or calibration mode in addition to a normal operating mode, which it enters automatically upon start-up or upon command. In this mode, it measures and records both the cold and hot resistances of the SMA. The controller may perform an initialisation or

calibration operation, either automatically upon being powered up or upon command, in which at least one test current is passed through at least one SMA element, at least one resistance measurement is made, and at least one operating parameter of at least one heating method is calculated from the resistance measurement.

Such a controller with a measurement capability is somewhat preferable to one without. Measuring hot (austenite phase) resistances implies heating up an actuator however, which in turn implies some movement, which may be undesirable. As such, if the hot resistance can be relied on as being a known scalar multiple of the cold (martensite phase) resistance, whereby the controller can get away with only a cold measurement, it may be preferable alternatively just to measure and record the cold resistance.

In another alternative, it may be possible to measure the relevant properties of an actuator before it is installed, or during the commissioning phase of a complete SMA actuated device or system.

In a practical embodiment according to the present invention, SMA actuators may be arranged in antagonistic pairs. When an initially stretched wire of one of the pair of SMA actuators having a largely martensite phase is contracted by heating, it exerts a stretching force on its cooler largely martensite phase antagonistic partner. Hence, as one of the wires contracts, the other of the wires is thereby stretched. This provides for the ongoing and substantially continuous operation of the actuators by the alternating heating of the wires without the need for a separate external mechanism for stretching the wires.

In one preferred embodiment, the controller further includes a motion control system for computing the desired degree of actuation of each actuator as a function of the discrepancy between a specified desired motion and a detected actual motion of the system as a whole. Typically such a motion control system would have access to other sensor data indicating the positions of various parts of the mechanical system under control. The gain of such a system may be set high so that anything more than a small position error will, after having been multiplied by the gain, result in a correctional signal that exceeds the safe limit current. When the measured resistance of each SMA portion is within the safe resistance range, thereby indicating the portion has not been overheated, the current applied across the portion will be the lesser of that determined by the correctional or command signal and the maximum limit current as may be determined by the electric power source. Thus, the calculation of the actuator current is accomplished in two stages, with the first producing a corrective signal in accordance with a motion control law, and the second clipping this value to somewhere within the range of zero to the maximum limit current.

Preferred embodiments according to the present invention allow a SMA portion to be held in a hot state (ie. largely austenite phase) should this become necessary with a current slightly lower than the safe limit current. This provides for lower average power consumption in such situations.

As such, the second current may be significantly less than the safe limit current quoted in, or deducible from, data sheets specifying safe heating currents for SMA materials, but still

large enough to maintain the SMA in its hot phase. By choosing a lesser current below the data sheet value, it is possible to reduce the power consumption of a SMA actuator during periods when rapid motion is not required.

The measured resistance may also be compared with values determined as the maximum and minimum allowable resistances for a functioning actuator. If the measured resistance falls outside the range defined by these, it may serve to indicate that the actuator has developed a fault.

In accordance with a further aspect of the present invention, there is provided a method of heating at least one SMA portion of an SMA actuator, the method including:

applying an electric current through the SMA portion; and

detecting change in the electric resistance of the SMA portion;

wherein

a first current above a safe limit current for the SMA portion is applied until a selected change in said electric resistance is detected and a second current less than said first current is applied after said change is detected.

Brief Description of the Drawings

Preferred embodiments of the present invention will now be described by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a front view of an antagonistic pair of SMA actuators according to an embodiment of the present invention;

Figure 2 is a schematic view of a controller for a SMA actuator according to an embodiment of the present invention.

Figure 3 is a graph of the electrical resistance of an approximately 0.1mm diameter wire that is approximately 1m long verses power during heating and cooling of the wire according to an embodiment of the present invention; and

Figure 4 is a graph showing both the input command position and the response position of the output shaft of the antagonistic pair of SMA actuators of Figure 1 under the control of a controller similar to that shown schematically in Figure 2.

Detailed Description

An antagonistic pair of SMA actuators 2, 4, generally indicated by the reference numeral 6, according to an embodiment of the present invention is shown in Figure 1. Each SMA actuator 2 (or 4) includes a SMA portion in the form of a wire 8 (10).

Each end of the wire 8 (10) is connected to an anchor point 12, 14 (16, 18). The anchor points 12, 14 (16, 18) both mechanically anchor the wire 8 (10) to a support base 20 and provide an electrical contact for applying an electric current from an electric power source (not shown in Figure 1) as will be later described. Each wire passes through an eyelet 22 (24). The eyelets 22, 24 are connected to the ends of a chord 26 that operably passes around a pulley 28, which is connected to an output shaft 30 that is rotably mounted to a bracket 32 that is mounted to an upper support 34. The pulley 28 and output shaft 30 may rotate in either of the directions indicated by the arrow denoted by reference numeral 36. In normal operation of the pair of SMA actuators 6, as will be further described below, the

wires 8, 10 are generally kept taut. In the case either of the wires 8, 10 become slack such as may occur if either of the SMA actuators 8, 10 are mechanically overloaded or a controller (not shown in Figure 1) for controlling operation of the SMA actuators 8, 10 is turned off however, guards 38, 40, 42 are provided to prevent the wires 8, 10, which conduct electrical currents during operation as will be described later, from touching and short circuiting.

A controller 44 suitable for controlling a SMA actuator 2 (4) according to an embodiment of the present invention is shown in figure 2. The controller 44 includes an electric power source in the form of a power supply 46 for applying an electric current through the wire 8 (10), a resistance sensor 48 to detect changes in the electric resistance of the wire 8 (10), a current regulator 50 for regulating the magnitude of the electric current applied across the wire 8 (10), a position sensor 52 for detecting the position of the SMA actuator's 2 (4) output element or the position of a mechanical component that is closely coupled to the SMA actuator's 2 (4) output element (for example output shaft 30), and a signal processor 54. The resistance sensor 48 includes a voltage sensor 56 for detecting the electric voltage across the wire 8 (10) and a current sensor 58 for detecting the electric current passing through the wire 8 (10).

In operation, the signal processor 54 receives a position command signal 60 from an external source (not shown), a position measurement signal 62 from the position sensor 52, a detected electric voltage signal 64 from the voltage sensor 56, and a detected electric current signal 66 from the current sensor 58. In response, the signal processor 54 outputs a

current command signal 68 to the adjustable current regulator 50 that regulates the current drawn from the power supply 46 that is applied across the wire 8 (10).

The electric current may be either AC (alternating current) or DC (direct current). In the case of DC it may be either a steady current or an intermittent one such as might be produced by a switch-mode regulator. In the case of AC or intermittent DC, references to the magnitudes of these currents are preferably taken to mean the RMS values rather than the peak or average values, as the primary consideration is how much heat the currents will produce. DC is preferable to AC in so much as it is generally easier to control and to make accurate resistance measurements.

One or more controllers similar to that shown in Figure 2 and described above may be used to rapidly heat the wires 8, 10 of the antagonistic pair of SMA actuators 6 shown in Figure 1, and thereby provide rapid rotation of the output shaft 30. In the view of the antagonistic pair of SMA actuators 6 shown in Figure 1, each of the wires 8, 10 are shown stretched half way between a minimum and a maximum operating strain for each wire 8, 10. If the wire 8 is heated by the application of a current through the wire 8 in response to a position command signal 60, the wire 8 will contract pulling on the eyelet 22 (downward as viewed in Figure 1) connected to the chord 26, thereby rotating the pulley 28 (and output shaft 30) in a clockwise (as viewed in Figure 1) direction and extending or straining the wire 10 a corresponding amount. If the wire 8 is allowed to cool and the wire 10 is then heated, the wire 10 will contract, rotating the pulley 28 and output shaft 30 in an anti-clockwise (as viewed in Figure 1) direction and extending the wire 8. As such, by the alternating heating

of the wires 8, 10, electric energy (or heat energy) may be used to perform mechanical work in the form of the reciprocal rotation of the output shaft 30. A controller according to an embodiment of the present invention provides for the rapid heating of the wires 8, 10 (and therefor actuation of the output shaft 30) without overheating and thereby permanently damaging the wires 8, 10, as will be described below.

In previously proposed SMA control systems (not shown), when heating a SMA portion the current passing through the SMA portion was not allowed to exceed a known safe limit current dependent on the exact proportions and composition of the SMA wires 8, 10. This limiting of the current was generally implemented by either a current regulator or a signal processor. In the former case, hardware within the current regulator prevents the current passing therethrough from exceeding a preset safe value, so that the actual current applied across the SMA portion is the minimum of the commanded current and the safe limit current. In the latter case, the signal processor first calculates a tentative current command signal, which is typically a function of the position error (the difference between the commanded position signal and the measured position signal). It then compares the tentative current command with the safe limit current for the SMA portion and computes the actual current command as the lesser of these two values.

In contrast, an embodiment of the present invention allows the SMA wires 8, 10 to be heated very rapidly, but without causing the overheating of the wires 8, 10. Large currents that are capable of overheating the SMA wires 8, 10, if applied long enough, are allowed to pass through the wires 8, 10 whenever the measured resistance lies within a predetermined

safe resistance range. Whenever the measured resistance lies outside this safe resistance range however, the current is restricted to the safe limit current for the wires 8, 10. The power supply 46 is capable of supplying, and the current regulator 50 capable of applying, a current substantially in excess of the safe limit current for the SMA wires 8, 10. The signal processor 54 calculates a tentative command current, but instead of comparing it with the safe limit current, the signal processor 54 calculates the resistance of the SMA (from the measured voltage 64 and current signals 66) and computes a safe maximum heating current as a function of the calculated resistance (as will be described below). The actual current command signal 68 is then the lesser of the tentative command current and the computed safe maximum heating current.

An example method for heating the wires 8, 10 according to an embodiment of the present invention is described below. Using wires 8, 10 in which the resistance drops as the material transforms from martensite to austenite phase, such as those formed from a nickel-titanium SMA such as nitinol for example, it is possible to identify a safe resistance in the form of a threshold resistance value R_{thresh} for a particular SMA portion that corresponds to a martensite ratio (the ratio of martensite phase present to austenite phase) close to but distinguishable from zero. This resistance, R_{thresh}, is used to mark the boundary threshold between resistance values that do imply that the wires 8, 10 are at a safe operating temperature and values that do not. In the case of nitinol for example, the former are resistances greater than or equal to R_{thresh} and can be described as safe resistances, since they imply that the SMA is not overheating. The latter correspond to

resistances less than R_{thresh}, and while these are not necessarily unsafe, there is the possibility that the SMA is overheating.

One practical procedure that could be employed as part of establishing R_{thresh} as part of an initialisation phase is to apply the safe limit current immediately and wait for the measured resistance value to stabilise. This value, when adjusted in line with a desired selected safety factor, can be used as R_{thresh}.

In a simple version of a heating strategy for the SMA wires 8, 10, according to an embodiment of the present invention the safe maximum heating current that may be applied to the wires 8, 10 at any particular time, I_{max}, may be calculated substantially continuously or at frequent intervals for example, according to the formula:

If $R_{meas} < R_{thresh}$

Then $I_{max} = I_{safe}$

Else $I_{max} = I_{high}$

Where R_{meas} is the measured electric resistance, I_{safe} is a current sufficient to heat the SMA but insufficient to overheat it such as the safe limit current, and I_{high} is a larger current intended to heat the SMA rapidly that may also be capable of overheating it. The value of the I_{high} should generally be chosen at or below the maximum capability (current limit) of the electric power source 46. From above, the actual heating current is therefor controlled in such a manner as to be always less than or equal to the calculated maximum I_{max}.

In another version of a heating strategy for the wires 8, 10, the calculation of I_{max} may be modified so as to make a smoother transition between I_{safe} and I_{high} over a range of resistances from R_{thresh} to a higher resistance R_{ramp}. The value selected for R_{ramp} will effect the behaviour of the system, but there are no particular constraints on its value other than being on the safe side of R_{thresh}. The selection of R_{ramp} involves a trade-off between a smooth transition of the actuator and the actuation speed. For example, a motion control law might require a smooth transition in order to achieve accurate trajectory tracking. The penalty for making the transition being too abrupt (R_{ramp} too close to R_{thresh}), needs be set off against the penalty for making the transition too prolonged (R_{ramp} too far from R_{thresh}), which is a loss of heating speed, and hence a loss of actuation speed.

By way of example, if it is desired that I_{max} vary linearly between these two resistances, R_{ramp} and R_{thresh}, then I_{max} may be calculated substantially continuously or at frequent intervals according to:

If $R_{meas} < R_{thresh}$

Then $I_{max} = I_{safe}$

Else if $R_{meas} > R_{ramp}$

Then $I_{max} = I_{high}$

Else

$$I_{max} = I_{safe} + \frac{(I_{high} - I_{safe})\ (R_{meas} - R_{thresh})}{R_{ramp} - R_{thresh}}$$

In a practical alternative used in experiments, a linear power ramp was used between R_{thresh} and R_{ramp}, which implies a nonlinear current ramp.

As previously alluded to, the controller shown in Figure 2 is suitable for controlling a single SMA actuator. If a system contains more than one SMA actuator then it is possible to control all of the actuators simultaneously by providing one controller for each. However, it is generally preferable to share certain elements of a controller among several actuators. In particular, it is practical to use a single power supply 46, or a small number of power supplies 46, to power all the actuators, and to use a single signal processor 54 to control all of the actuators in the system, or one signal processor 54 per subsystem. For example, if a single signal processor 54 were in charge of both the actuators 2, 4 in the antagonistic pair 6, then it could use a motion control law that was specifically designed for antagonistic pairs 6.

The design of the controller 44 advantageously allows for an inaccurate current regulator 50 (i.e., one in which the actual current is only approximately equal to the commanded current). The signal processor 54, having a current feedback loop, can compensate for any inaccuracies in the regulator 50 by comparing and issuing an adjusted current command 68 to the current regulator 50 so as to bring the actual current closer to the desired value.

After sufficient heating such that the wire 8 has a substantially 100% austenite phase, the wire 8 is then cooled or allowed to cool such that it reverts to having a substantially 100% martensite phase with a constant initial length. While the rapidity at which the wire 8 cools will be dependent on both the properties of the alloy used and the geometry of the wire 8, as previously indicated this may be improved by water-cooling or fan-forcing air across the surface(s) of the wire 8.

An electric current may then be applied across the stretched wire 10 to heat the wire 10. This similarly results in the wire 10 reverting or contracting to its initial length or shape, thereby rotating the shaft in a counter-clockwise direction and stretching the wire 8. As such, by the alternate heating of the wires 8, 10 by the application of selected electric currents, the antagonistic pair of SMA actuators 6 provides reciprocating rotation of the output shaft 30 to perform mechanical work.

It will be appreciated alternatively that the stretched wire 10 may alternatively be heated while the contracted wire 8 is cooling but is still hot, provided the wire 8 has cooled down sufficiently by the time the wire 10 is fully heated

While the safe resistance or the threshold resistance level, R_{thresh}, for each wire 8 (10), this can be determined empirically during the set up, preferably it is calculated automatically each time on start-up of the actuator 2 (4) for example, or on command. This can be done by calculating the hot and cold resistance of the wire, 8 (10) before proceeding to carry out motion commands. This would allow any variation in the resistance levels of the SMA wires 8, (10) to be compensated for by the controller 44.

Figure 3 is a graph of electrical resistance of a 0.1mm diameter nitinol wire, approximately 1 meter long, against electrical heating input power during heating and cooling of the wire. A very slow power ramp was applied to the wire, starting at 0 watts (where at the wire has a substantially martensite phase) and increasing the power (or applied current) at a rate of 0.1 watts per second to a power level of 4.8 watts just off the edge of the graph in Figure 3

(where at the wire has a substantially austenite phase), and then decreasing the power at 0.1 watts per second to zero (where at the wire again has a substantially martensite phase). The slow rate of power change ensures that the wire is always very close to its equilibrium temperature for the power level being applied. Thus, the temperature of the wire when the power reaches 2 watts (for example) on the rising or increasing ramp, corresponding to the curve indicted by reference numeral 70, is almost the same as the temperature of the wire when the power reaches 2 watts on the falling or decreasing ramp corresponding to the curve indicated by reference numeral 72. Direct measurement of the temperature of the wire is relatively difficult compared with measuring the electrical input power, so in experiments the latter was used as a proxy for the former.

The graph in Figure 3 shows the two relevant properties of this and other similar SMAs: (1) a resistance change caused by the phase change within the material , and (2) the thermal hysteresis of the phase change.

Starting with the wire cold, and therefore in a mostly martensite phase, the resistance of this particular wire is 116 ohms. As the wire is heated (see curve 70), the resistance begins to drop as the power level reaches 1.7 watts. This indicates that the material has reached the temperature at which martensite phase material begins to transform into austenite. This is typically known in literature as the austenite start temperature (or A_s). As the power level continues to rise, the resistance drops sharply and bottoms out at around 101 ohms at around 4 watts, although it has very nearly bottomed out at around 3.5 watts. At this point

(ie. about 3.5 watts), the wire has reached the austenite finish temperature (or A_f) and the transformation from martensite to austenite is substantially complete.

Upon cooling (see curve 72), the resistance begins to rise as the power level drops to about 3 watts, and it rises steadily to a maximum of around 119 ohms at a power level of about 0.3 watts. Resistance measurements for power levels close to zero have been omitted as they were considered inaccurate. It will be appreciated that the discrepancy between the initial and final cold resistance indicates that the wire is not quite in the same physical state after the power ramp as it was before. Nevertheless, the wire does begin and end in a mostly martensite state.

Because of the thermal hysteresis in the material as previously discussed, the changing temperature of the material cannot be deduced exactly from its resistance, but it is possible to identify a range of temperatures that are consistent with the measured resistance. For example, if the resistance measurement is 110 ohms then the temperature must be somewhere between the equilibrium temperature for 1.4 watts of heating and the equilibrium temperature for 2.5 watts of heating. Further, if the resistance is 110 ohms or higher then the temperature of the wire must be at or below the equilibrium temperature for 2.5 watts of heating.

The datasheet value for the safe limit current for the particular wire tested corresponds to a power lever of approximately 3.5 watts. While this safe limit current is exceeded in this

particular experiment, it is not enough to cause significant thermal damage. Thus, any temperature below the equilibrium for 3.5 watts can be regarded as safe.

For embodiments of the present invention, a safe resistance corresponding to a resistance that rules out the possibility of overheating, with a desired safety margin in the value of the resistance needs to be determined. If the resistance of a SMA portion drops during the phase change, and the resistance of an overheated portion does not exceed 100 ohms, for example, and a safety margin of 1% is desired, then a value of 101 ohms (being 1% greater than 100 ohms) can be used as the threshold between safe resistances (>=101) and possibly-unsafe resistances (<101). The safety margin allows for anticipated noise or inaccuracy in the resistance measurement, and for the expected variation in the wire's resistance due to varying strain as described below. In experiments, a safety margin of around 4%. was used.

For the particular wire having the resistance profile shown in Figure 3, the temperature of the overheated wire does not exceed 101 ohms. The selected value of the threshold resistance, R_{thresh}, should therefore be a value greater than this by a desired safety margin. The safety margin should be sufficient to allow for possible noise and inaccuracies in resistance measurements, and strain-induced variations in the resistance of the wire. In experiments, strain induced variations in the resistance were accounted for by calculating an upper bound (at the time the actuator is designed) on the magnitude of the strain-induced resistance change at the relevant temperature, and factoring this into the safety margin for the threshold resistance R_{thresh}. Alternatively for example however , data from

the position sensors 52 can be used to calculate the actual strain, at least approximately, and hence the resistance change due to strain. This can then be subtracted from the measured resistance value to get a strain-compensated resistance measurement.

Figure 4 is a graph of the tracking response of a system comprising the antagonistic pair of actuators 6 shown in Figure 1 under the control of a motion control system similar to that shown in Figure 2.

The graph in Figure 4 shows the response of the system to a motion command signal consisting of a 1 Hz sine wave of amplitude 30 degrees. This command signal is shown as a dashed line indicated by reference numeral 74. The solid line shows the angle of the output shaft 30 in response to this command signal and is indicated by the reference numeral 76. To begin with, the controller 44 limits the current to the safe limit current specified in the data sheet for the type of SMA wire (nitinol) used, which is 0.18 amps, as per previously proposed heating methods.

After 30 seconds, the controller switches to a heating method according to an embodiment of the present invention. In this case, the heating current is limited to the 0.18 amps whenever the measured resistance is below 105 ohms, and is limited to the larger value of approximately 0.42 amps (which delivers around 20 watts of Joule heating to the wire) whenever the measured resistance is above 118 ohms. In between these two resistance values, the maximum heating current varies between 0.18 and 0.42 amps in such a way

that the heating power varies linearly with resistance (ie. the controller implements a linear power ramp from 3.5 watts at 105 ohms to 20 watts at 118 ohms).

As can be seen in Figure 4, the actuator 6 moves much more quickly (steeper slope) after the 30 second mark, indicating that the rapid heating method according to an embodiment of the present can produce a substantial improvement in the maximum velocity of actuation.

It will be appreciated that SMA actuators according to embodiments of the invention could take many forms. Alternatively for example, a plurality of antagonistic pairs working together may be provided, or the wires can instead be coils. In a further alternative form, an SMA actuator according to an embodiment of the present invention can include one or more wires that may be heated together to provide for the movement of an actuating element during shape recovery of the wires substantially in the one direction, such that the actuator may provide a greater force. The external force supplied to stretch the wires.when they are relatively cool and close to 100% martensite phase can be provided for example, by separate SMA actuators, or further alternatively by one or more springs or weights that stretch the wires after cooling from a largely austenite phase to a largely martensite phase.

The above embodiments of the present invention have been described by way of example only and modifications and variations may be made without departing from the spirit and scope of the invention described. Further, it will be appreciated that remarks in the drawings are exemplary only.

Throughout the specification, unless the context requires otherwise, the word "comprise", and variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated step or integer or group of steps or integers but not the exclusion of any other step or integer or group of steps or integers.

The reference to any prior art in this specification is not, and should not be taken as, an acknowledgement or any form of suggestion that that prior art forms part of the common general knowledge in Australia.

DATED this 9th day of February 2004

IN THE NAME OF

ANUTECH PTY. LIMITED

By its Patent Attorneys:

DAVIES COLLISON CAVE

Figure 1

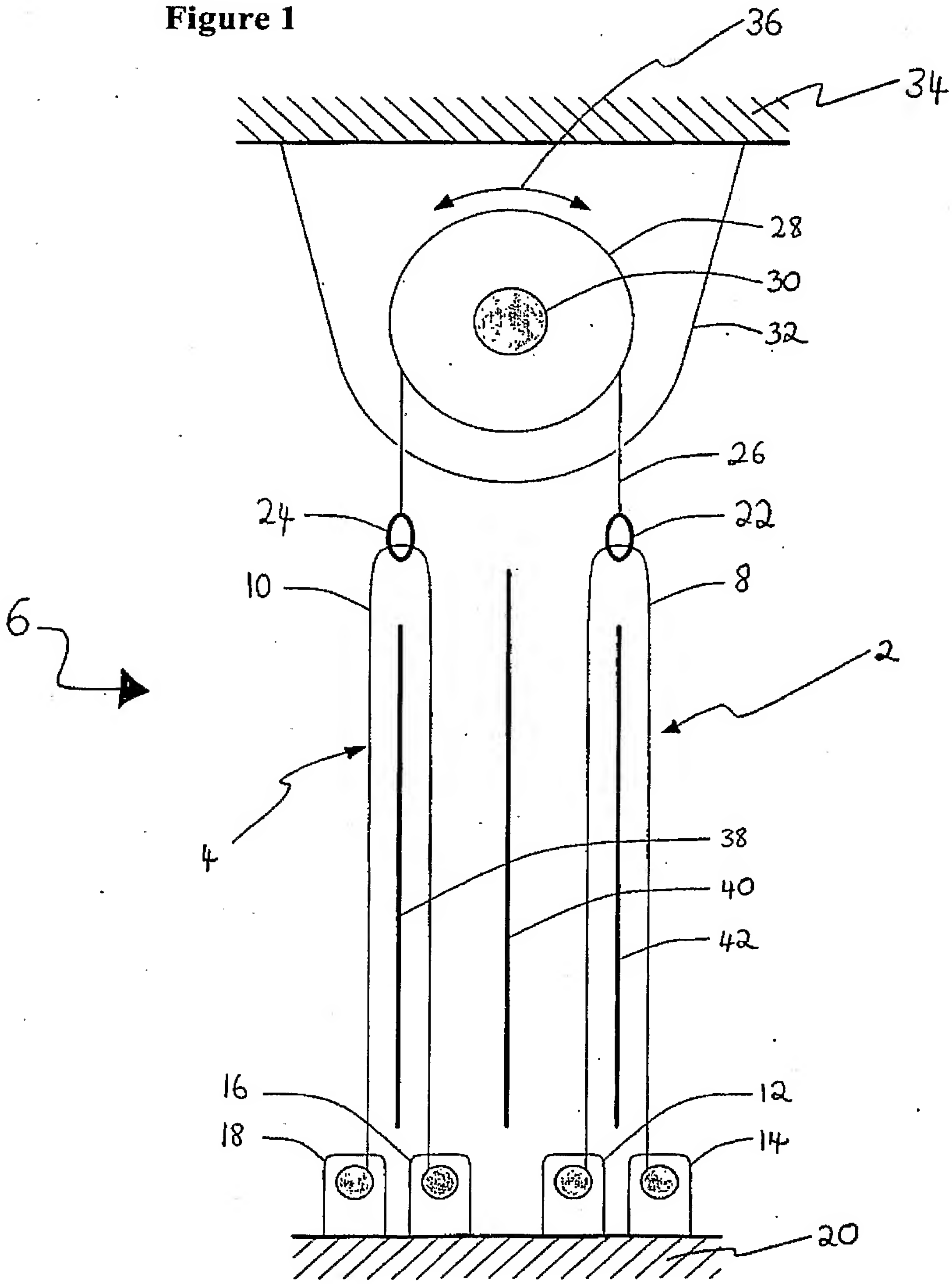


Figure 2

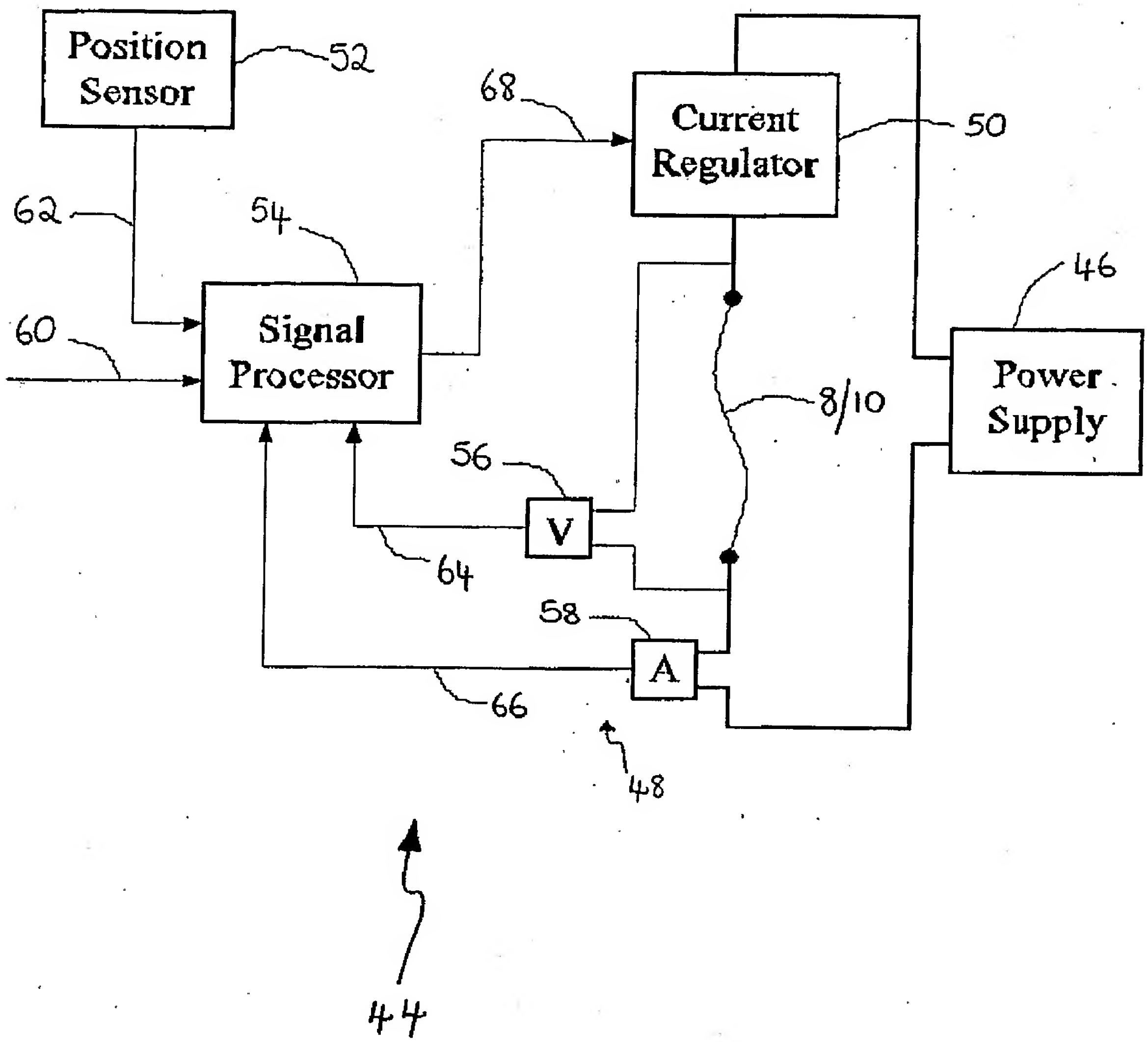
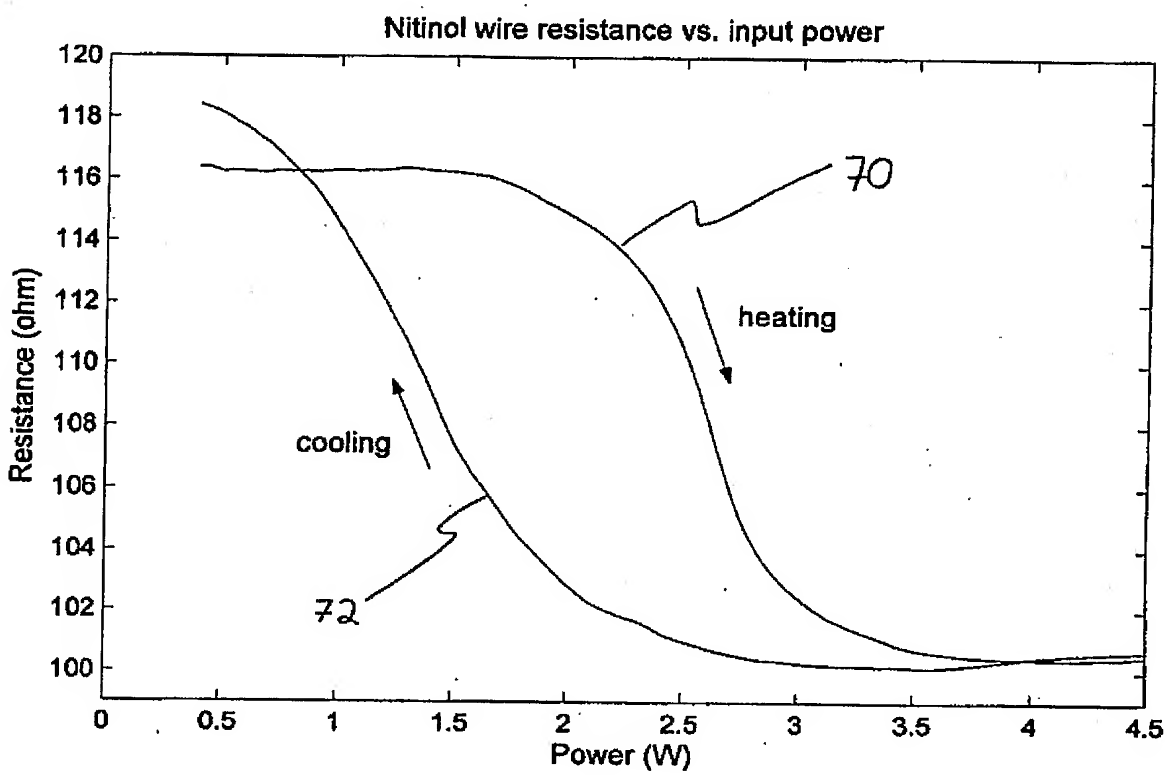
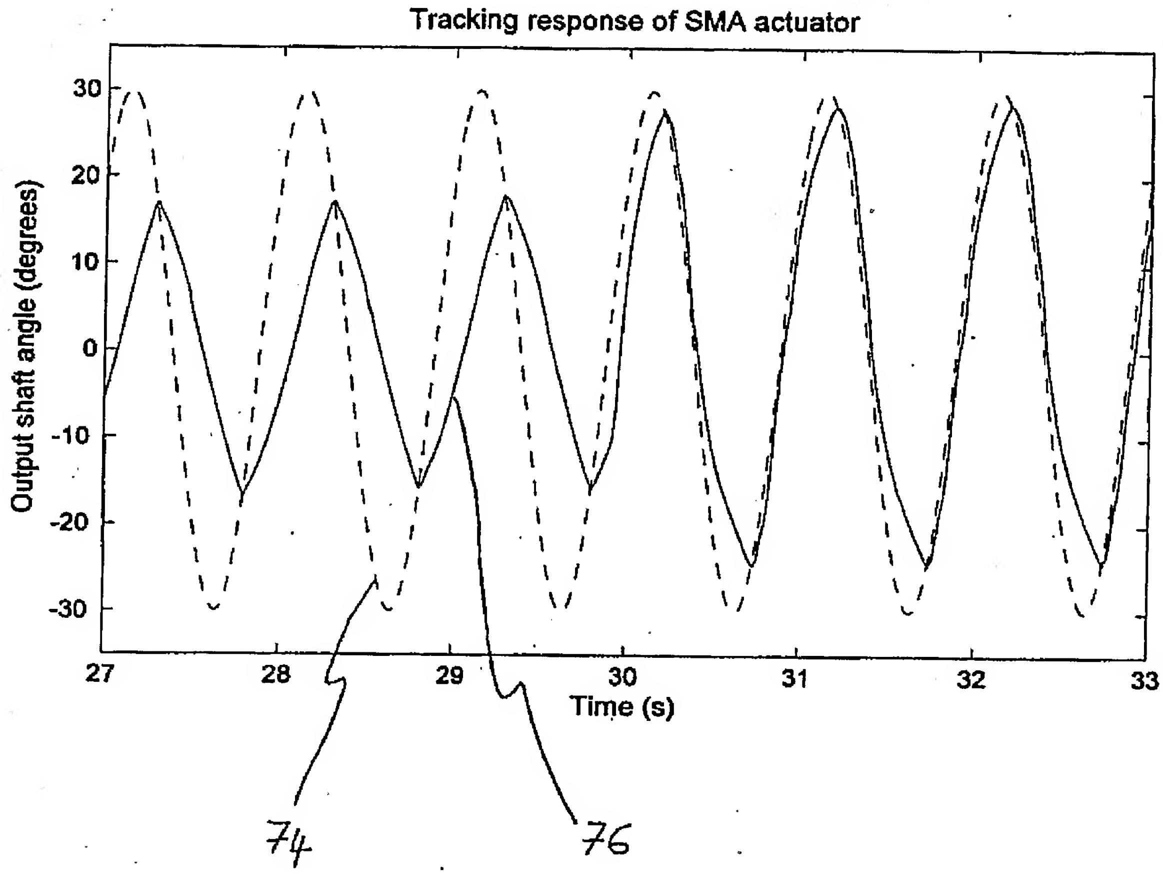

Position Sensor
52
68
Current Regulator
50
62
54
60
Signal Processor
46
8/10
Power Supply
56
V
64
58
A
66
48
44

Figure 3



Nitinol wire resistance vs. input power
Resistance (ohm)
120
118
116
114
112
110
108
106
104
102
100
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Power (W)
70
heating
cooling
72

Figure 4


Tracking response of SMA actuator
Output shaft angle (degrees)
30
20
10
0
-10
-20
-30
27
28
29
30
31
32
33
Time (s)
74
76